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# CONTROLLED COMBUSTION OF WASTE MATERIAL IN COMPACT DUMP COPMBUSTORS

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Final Report for the Period
October 1994 - December 1995
Grant No. N00014-95-1-0163

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A large-eddy simulation (LES) model was developed to simulate waste injection and combustion in a compact dump combustor. The configuration and the dimensions of the modeled was chosen to correspond identically to the experimental device. The first phase of the study investigated non-reacting fuel-air mixing in the combustor. The fuel (here considered to represent the waste) was injected using both passive and active control of the injection process. The pressure field in the combustor was used as a sensor and the fuel was injected both in-phase and out-of-phase with the local (at the dump plane) pressure oscillation. Results showed that when fuel (or waste) is injected in-phase with the local pressure oscillation (that is when the pressure is higher than the mean), then significantly enhanced entrainment of the fuel into the large coherent structures in the shear layer can occur. Engulfment of the waste into the vortices can increase the waste residence time in the combustor and hence increase its consumption. Results with and without heat release confirm this observation - results are in good agreement with the observation in the laboratory.

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## INTRODUCTION

This report summarizes the results obtained during the first year of this project. Since the initial project was initiated as a one-year project, the present final report is being submitted as required under the contract. The project has made significant progress in the study of controlled waste injection into dump combustor for enhanced combustion. A similar report was submitted in December 1995 as a part of the continuation proposal to SERDP program. In the following, the highlights of this study are briefly discussed.

## OBJECTIVES:

The overall objectives of this study were to

[1] Numerically investigate active waste injection and control strategies to enhance waste combustion in compact incinerators identical to experimental devices.

[2] Use simulation data to understand and optimize the injection method.

[3] To devise simple process models that can used for design parametric studies.

## FIRST YEAR'S PROGRESS:

The progress made in the first year's study is summarized below.

*[1] Validation of the baseline LES code*

The LES simulation model used for this study was re-validated to confirm its predictive capability. In addition, since the present simulation model is fully operational on massively parallel machines such as the Intel Paragon, IBM SP-2 and the Cray T3D, the validation of the model also served as a validation on these machines. The basic LES scheme solves the axisymmetric, unsteady compressible Navier-Stokes equations using an unsplit finite-volume MacCormack scheme. This scheme is second-order accurate in time and fourth-order accurate in space. There are two subgrid models implemented in this code: an algebraic eddy viscosity model similar to the one developed earlier and a one-equation model for the subgrid kinetic energy. For the preliminary studies, only the algebraic subgrid model has been employed since it is computationally

inexpensive. Furthermore, since in 2D or axisymmetric turbulent flows, the energy cascade process is significantly altered, this has significant implications for the implementation of the subgrid kinetic energy. Also, to ensure proper development of the subgrid kinetic energy, the kinetic energy initialization at the inflow must be carried out correctly. This information is currently unknown, and therefore, these validation studies were carried out using the simpler eddy viscosity model.

*[2] Large-eddy simulation of waste injection and combustion:*

A large-eddy simulation (LES) model was developed to simulate waste injection and combustion in a compact dump combustor. The configuration and the dimensions of the modeled was chosen to correspond identically to the experimental device. The first phase of the study investigated non-reacting fuel-air mixing in the combustor. The fuel (here considered to represent the waste) was injected using both passive and active control of the injection process. The pressure field in the combustor was used as a sensor and the fuel was injected both in-phase and out-of-phase with the local (at the dump plane) pressure oscillation. Results showed that when fuel (or waste) is injected in-phase with the local pressure oscillation (that is when the pressure is <u>higher than the mean</u>), then significantly enhanced entrainment of the fuel into the large coherent structures in the shear layer can occur. Engulfment of the waste into the vortices can increase the waste residence time in the combustor and hence increase its consumption. <u>Results with and without heat release confirm this observation - results are in good agreement with the observation in the laboratory.</u>

Analysis for the simulation results showed that when the pressure is high, the local forward (axial) motion of the shear layer is inhibited considerably and the vorticity in the shear layer "piles" up near the base of the dump, and when the pressure drops and the axial velocity rapidly increases, this concentrated shear layer rolls up into a large coherent vortical structure. Thus, when fuel is injected into the shear layer in-phase with the pressure fluctuation, the injected species is directly entrained into the shear layer that forms the primary core of the large vortices.

In the second phase of this study, a larger combustor design (again similar to the experimental test rig) was modeled. The test conditions were again chosen identical to the experimental values. Ethylene was used as the fuel and benzene was the surrogate waste for this study. Figure x summarizes the test geometry and test conditions. To excite the large vortex structures, the inflow air stream was forced at the frequency measured in the experiments. Again, non-reacting studies confirmed that in-phase (with the inflow forcing) injection of the waste/fuel resulted in significant entrainment of the waste into the shear layer. To model the chemistry, a global kinetic mechanism was used and for the initial study, a relatively slow chemical rate was employed. The slow chemistry approximation was employed to reduce the computational cost and for quick turnaround of the results. Results showed that nearly 99% of the injected waste is consumed within 2-3 step heights downstream of the dump plane. However, due to the slow consumption simulated in the study, this rate was found to be slightly lower that the measured data. This discrepancy was directly related to the chemical rates and current effort is directed towards simulating more detailed reactions using realistic chemical rates.

To study more realistic combustion, the full chemical rate for the ethylene and benzene will be used for the next stage of simulations. These simulations will be carried out in the second year of this project.

*[3] Development of engineering models:*

In parallel to the above LES study, research effort is being directed towards developing an engineering model for design analysis. Two independent efforts, which will be eventually combined, are currently underway: (a) a study of fuzzy control for active control, and, (b) a one-dimensional model development based on the LES result. These efforts are briefly described below.

<u>(a) Fuzzy Active Control:</u>

In this effort, an experimental reheat buzz device studied extensively at Cambridge University is being used as a test configuration. At Cambridge, both experimental and numerical studies of active control have been carried out on this device and therefore, there is significant amount of information available for fuzzy control validation. In fuzzy control applications, the active control rules are not precise, rather they are chosen to vaguely (fuzzy) represent the sensor and control effects. A steady state one-dimensional model for the mean flow is being used along with a 1D unsteady model for the perturbation. The effects of mass injection and heat injection (by secondary fuel injection) have been first studied in both open and closed loop manner to first understand the effects of control and to confirm that the present model predictions are in agreement with the studies at Cambridge. The information obtained from these simulations was then used to device fuzzy rules for pressure sensing and for both mass and fuel injection. Preliminary results clearly show that the fuzzy controller is capable of achieving control of the pressure fluctuation amplitude. These results are in good agreement with the past studies using both open and closed loop control. In particular, the fuzzy controller showed promise for achieving control even for test conditions that were not studied earlier. It is this particular aspect of the fuzzy control method that is very interesting since this implies that the fuzzy controller is capable of learning/adjusting to new test conditions/configurations without a significant learning curve. The model studies are still underway (some results will be reported soon) and further refinements are required (and will be carried out next year) before this type of controller can be used for dump combustors.

<u>(b) One-Dimensional model of the LES model:</u>

The LES method is extremely time consuming and cannot be used for engineering design analysis. Therefore, an effort is underway to develop a simplified 1D model for the dump combustor which incorporated within it the unsteady aspects of the fuel/waste injection, the vortex motion, and the unsteady heat release. The mean flow and the unsteady perturbations are being modeled by simplifying the governing equations. The unsteady data from the LES is being used to develop the inflow/outflow boundary conditions. A linearized analysis is being used to identify the energy carrying modes in the flow (e.g., the acoustic modes). This effort has just begun and results are expected in the next few months.

Once the 1D model of the LES results is developed, the fuzzy control method developed using the reheat buzz study will be extended and integrated within the 1D dump combustor model. The fuzzy control rules will have to be further refined to correspond to the dump combustor behavior. For this purpose, the LES results will be used.

## WORK PLAN PROPOSED FOR THE SECOND AND THIRD YEAR EFFORT

In the following, the tasks associated with the research effort for the second and third year of this study are briefly discussed. Many of the following research tasks will be carried out in parallel and therefore, progress (time) estimates indicated below are for each task.

[1] Demonstration of the Fuzzy Controller for Reheat Buzz Control: This task is almost complete and is expected to be finished within the next 2-3 months. This demonstration will involve comparison with the past experimental and numerical results (obtained at Cambridge U) and then utilizing the fuzzy controller to study reheat buzz control using secondary fuel injection in test devices that were not studied earlier.

[2] Fuzzy Controller for Fuel Injection and Non-Premixed Combustion: The reheat buzz study described above assumes that the fuel-air is premixed and combustion occurs in a premixed mode. However, this is not the situation in the current waste burning dump combustor. Therefore, the controller developed above needs to be modified to allow for fuel injection and to include a time-delay for fuel-air mixing. The reheat buzz device simulated above will be used for this study and the combustion process will be modified to model fuel injection and the effects of non-premixed combustion. Model constraints for fuel injection and mixing time scales will be obtained from the analysis of the LES results. We expect this effort to take around 6-7 months.

[3] Extension of the Les Model to include Two-phase Combustion: The toxic material could be in any form -gaseous, liquid or solid. To simulate realistic waste combustion, the current gas-phase LES model needs to be extended to simulate two-phase flows. We will follow known methods for this purpose and employ simplified models (developed in gas turbine research) to incorporate the effects of liquid jet breakdown, vaporization and ignition delay into the current LES model. The extension to two-phase flow and the preliminary validation of this model for simplified flow conditions (e.g., mixing layers) is expected to take around 7-8 months. We are also going to investigate if a commercial available code, for example, KIVA-3 can be utilized for this phase of study. This code is being considered since it has the state-of-the-art implementation of two-phase models for liquid fuel injection, vaporization and mixing, etc. In addition, it is also capable of simulating flow in complex three-dimensional domains. This capability is particularly interesting if highly 3D flows in the compact waste incinerator devices needs to be simulated.

[4] Revisit Injection Strategies for Two-phase Combustion: The injection strategies developed using the gas phase studies will be revisited for application to liquid fuel/waste injection and combustion. Some simplifications of the submodels will be required to handle this complex process for phase change and mixing process. These issues will be addressed in this task.

[5] Incorporate Realistic Waste Chemistry into the LES Model: More detailed waste kinetics will be developed and incorporated into the LES model. However, it is worth noting that in some cases, the waste reaction mechanism is expected to be unknown. Therefore, the experimental results will be used to develop reduced reaction mechanism that will attempt to model the waste combustion without significantly increasing the computational cost. This effort is expected to be an ongoing effort in the next two years and the waste models chosen for simulations will depend upon the experimental approach.

[6] Development of the 1D Unsteady Model of the Dump Combustor: The effort currently underway to develop the 1D model for the LES results will be completed in the next few months. This model will utilize the current LES results to incorporate the unsteady features of the flow and combustion processes. The prediction of the 1D model will be validated using the LES results. Once validated, further extensions to the model to allow for two-phase effects will be incorporated. The final model will also be validated using the LES data and the new experimental data when it becomes available. The effects of both steady and unsteady fuel and waste injection will be modeled using simplified injection rules developed from the LES results. This effort is expected to be ongoing for the next two years as the research direction will be determined by the experimental requirements and conditions.

[7] Integration of the Fuzzy Controller into the 1D Unsteady Model: The fuzzy controller developed the earlier tasks will be incorporated into the 1D unsteady model. The fuzzy rules will be modified to correspond to the results obtained in the dump combustor from both the LES and experimental studies. The behavior and the ability of the fuzzy controller in achieving and enhancing controlled combustion will be evaluated.

[8] Demonstration of the 1D Engineering Model for Design Applications: The ability of the 1D unsteady model (including the fuzzy controller) will be evaluated in this task. The key goal of this research is to develop a simple yet accurate model that will be numerically economical for engineering design analysis. The validation of this model will provide confidence in its predictions. Subsequently, this model will be used for parametric design analysis.

**Publications/Presentations:**


1. Srinivasan, A. and Menon, S. (1994) "A Numerical Study of Fuel Injection Control in Dump Combustors," presented at the 1994 Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Atlanta, GA, November.

2. Menon, S. and Sun, Y. (1996) "Fuzzy Logic Control of Reheat Buzz", to be presented at the 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Meeting, Orlando, Fl, July 1-3.

3. Srinivasan, A. and Menon, S. (1996) "Simulation of Controlled Injection of Toxic Waste for Enhanced Destruction in Compact Incinerators", to be presented at the 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Meeting, Orlando, FL, July 1-3.